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ABSTRACT

A procedure for detecting and displaying a measure of the acoustic coupling through the velopharyngeal port during speech was developed. The procedure was used with nine deaf students to train for velar control in both unsupervised and tutorial drills. Results showed that tutoring with the display resulted in acquisition of new speech skills, including ability to produce vowels in isolation, in words, and in phrases with proper control of the velum. Objective evaluations demonstrated that eight of the nine students showed various amounts of improvement. (SK)

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USE OF A VISUAL DISPLAY OF NASALIZATION TO FACILITATE TRAINING OF VELAR CONTROL FOR DEAF SPEAKERS

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14 September 1974

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Abstract

A procedure for detecting and displaying a measure of the acoustic coupling through the velopharyngeal port during speech is presented, and application of the procedure to the speech training of deaf students is described. Experience in the training of velar control with nine deaf students is discussed, including use of the display in unsupervised drill as well as in a tutorial situation. Results show that tutoring with the aid of the display results in the acquisition of new speech skills, including the ability to produce vowels in isolation, in words and in phrases with proper control of the velum. Objective evaluations of the speech of the students before and after training (and, in some cases, at different times within training) demonstrated that eight of the nine students showed various amounts of improvement, in the sense that more vowels were apparently produced with a raised velum after training, both in isolated words and in sentences. For four of these students, subjective judgments of adequacy of velar control for sentences also showed improvement, whereas for the others it did not. It is concluded that training with the display can lead to more adequate velar control in the speech of most deaf children who are diagnosed to have problems with this aspect of their speech. There is need for the development of training procedures that will accelerate the carryover of these skills to spontaneous speech.

Use of A Visual Display of Nasalization to Facilitate Training of Velar Control for Deaf Speakers

K. N. Stevens, R. S. Nickerson, A. M. Rollins,
and A. Boothroyd

Proper control of the velum is a difficult speech skill to acquire in the absence of auditory feedback, because the gestures of raising and lowering the velum are not visible, and such proprioceptive cues as exist do not seem to be cognitively meaningful. Most people are not conscious of velar movements, and they learn to make them only because they can hear the acoustic consequences of these movements. As a result, the speech of the deaf is often characterized by inappropriate nasal qualities. Improper control of the velum has long been recognized as a source of difficulty in the speech of the deaf (Brehm, 1922; Hudgins, 1934). If the velum is not raised during the production of vowels and consonants that normally are nonnasal, the resulting speech will have a hypernasal sound for a listener. If the velum is raised during the attempted production of nasal consonants (/m, n, ŋ/), stop consonants rather than nasals may be heard, and the speech will have a hyponasal quality.

An approach that has been taken in attempts to remediate this type of problem is that of providing the deaf speaker with visual

cues that relate in some relatively direct way to the degree of nasalization in speech sounds. (See, for example, Fletcher, 1970; Holbrook & Crawford, 1970; Stevens, Nickerson, Boothroyd, & Rollins, 1974). The purpose of this note is to present the results of one such attempt to use a visual display of nasalization as an aid for training of velar control for several deaf students.

SYSTEM FOR DISPLAY OF NASALIZATION

The display is one of the set of training aids that comprises a computer-based system that has been described elsewhere (Nickerson & Stevens, 1973; Nickerson, Kalikow, & Stevens, 1974). The important features of the system, for the purposes of this paper, may be summarized as follows. (1) Nasalization[1] is detected by a miniature (1.8 gms) accelerometer attached by two-way adhesive to the nose (Stevens, Kalikow, & Willemain, 1974). The output of the accelerometer is fed, after suitable preprocessing, to the computer, which generates and maintains the visual display. (2) The display shows the amplitude of the accelerometer output as a function of time. (3) In addition, the display gives an indication of voicing; in particular, whenever the utterance is voiced, a horizontal line appears at the base of the nasalization function. (4) A criterion line can be displayed along with the nasalization curve, to indicate to the student a particular nasalization value above, or below, which he should attempt to keep his trace, depending on whether the utterance or some portion of the utterance should be

nasal or nonnasal. (5) The displayed curve moves from right to left in real time, the current instant of time being represented by a fixed location to the right of the screen. (6) A reference display can be generated by the teacher, and this display remains frozen on the upper half of the screen when the student attempts an utterance. The trace representing the student's utterance appears on the lower half of the screen. (7) The past two seconds of the display can be frozen on the screen by depressing a button, and this stored display can be replayed, together with the audio speech signal. (8) The option exists of either generating the display in real time (flow mode), or delaying the presentation of the display (delay mode) until the utterance is completed and the teacher (or student) depresses a button. (The latter option was incorporated in the system during the course of the speech-training activities reported here, and hence was not available in the training sessions for all students.)

Measurements using this type of accelerometer and display have been made for normally-hearing speakers producing various utterances containing nasal and nonnasal sounds. The data show that this system is capable of discriminating nasal from nonnasal sounds. The accelerometer output is usually about 15-20 dB greater for nasal consonants and nasal vowels than for nonnasal vowels (Stevens, Nickerson, Boothroyd, & Rollins, 1974); this difference depends to some extent on the vowel, being greater for low vowels than for high vowels.

Examples of the display that was used in the diagnosis, training, and evaluation of the deaf children are shown in Figs. 1 and 2. The displays in Fig. 1 represent the words sam and pad produced by a deaf child. The accelerometer output in the nonnasal word was only 5 dB below that for the nasal consonant in sam--substantially less than the 20-dB difference established as a criterion for this vowel on the basis of measurements from normally-hearing children. (As noted earlier, it is possible to display a horizontal criterion line along with the nasalization trace, indicating the nasalization value. The criterion line is not shown in these figures. This objective assessment of excessive nasalization was supported by judgments of two teachers that the word pad had a nasal quality. The onset of significant output from the nasal accelerometer lags behind the onset of voicing in this example, indicating that the velum was probably closed during the stop consonant (a necessary requirement for buildup of positive intraoral pressure), but that velopharyngeal opening occurred shortly after the drop in intraoral pressure following the consonantal release.

Comparison of the display for a normally-hearing adult and a deaf child producing the word Monday is shown in Fig. 2. For both speakers, the peaks in the trace for the two nasal consonants are evident, and the vowel between these consonants is somewhat nasalized, as expected. The deaf child also nasalizes the second vowel, shortly after the release of the stop consonant /d/, whereas the hearing speaker apparently produces this vowel with a closed velum. Some

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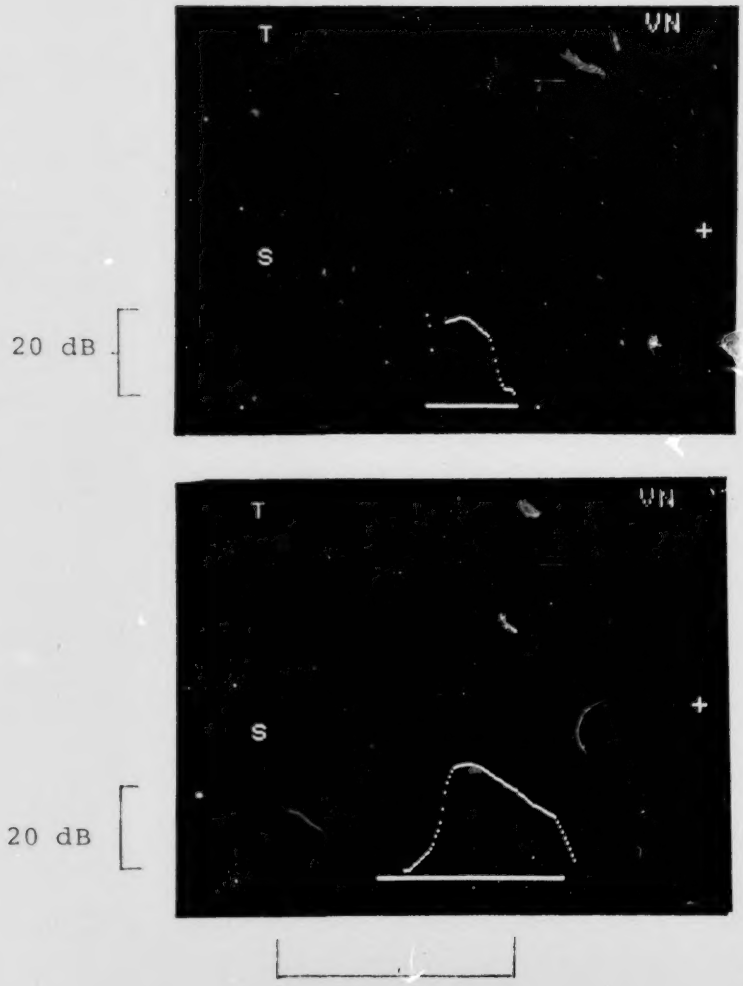

Fig. 1. Voicing nasalization display for the words pad (top) and sam (bottom) produced by a deaf student who has problems with velar control. The horizontal line at the bottom of the display indicates when voicing is present. The curve is the amplitude of the output of the accelerometer attached to the nose (on a logarithmic scale). This student produces excessive nasalization in the nonnasal word, but is able to close the velum during the obstruent consonants, as shown by the lack of nasalization immedidately following the release of /p/ and of /s/.

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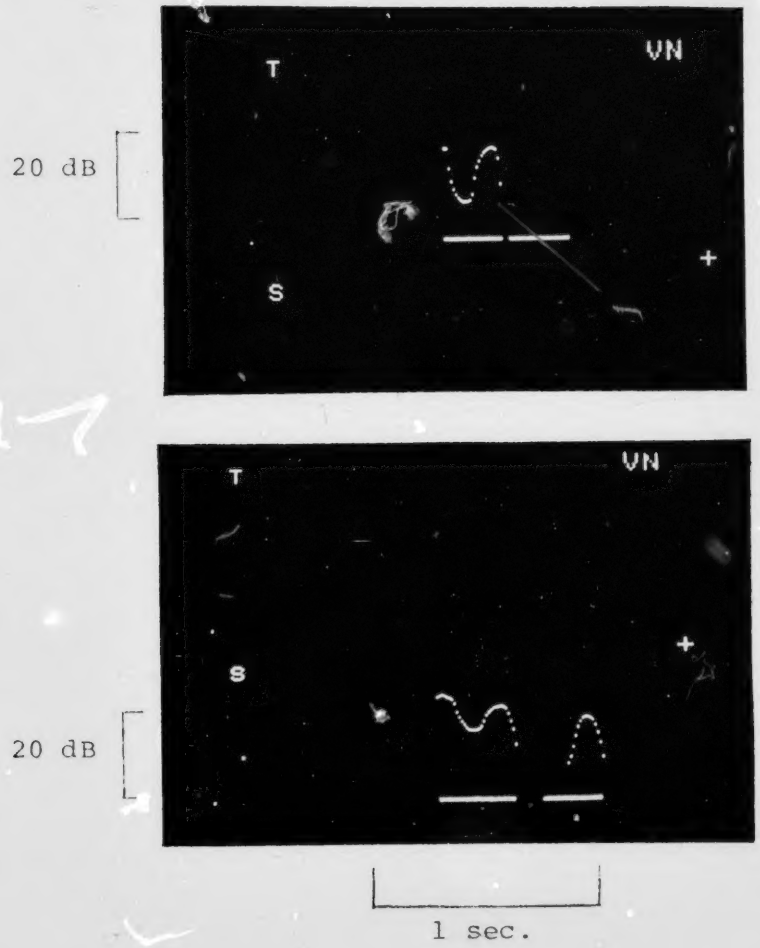

Fig. 2. Voicing-nasalization display for the word Monday, as produced by a normally-hearing adult (top) and a deaf student (bottom).

deaf children exhibit hyponasality, in which case the display shows little or no accelerometer output throughout the utterance, and the word sounds like [bʌdI].

Examples of the displa, for the more complex utterance "You can drink your milk" are given in Fig. 3. The deaf child in this case generates the first word with excessive nasalization, and also does not produce an interruption of voicing in the /k/ of drink, possibly as a consequence of failure to raise the velum for this sound.

In the course of training of the deaf children, we had occasion to record certain utterances which were produced with excessive nasalization and also without apparent nasalization by the same child, as determined both from measurements of the accelerometer signal and subjective impressions of listeners. Examples of spectrographic data from two such utterances are shown in Figs. 4 and 5. Spectra of the vowel in the word four, produced with and without nasalization, are given in Fig. 4. These spectra were generated with a filter bank having relatively wide filter bandwidths (360 Hz) at low frequencies, and consequently details of the vowel formant structure are somewhat smoothed. The spectrum for the nasalized vowel shows a spread of energy in the first-formant region, presumably as a consequence of the splitting of the first formant that occurs when acoustic coupling to the nasal cavity is introduced (House & Stevens, 1956). The resulting additional resonance at low frequencies, below the frequency of the nonnasal first formant, combines with the

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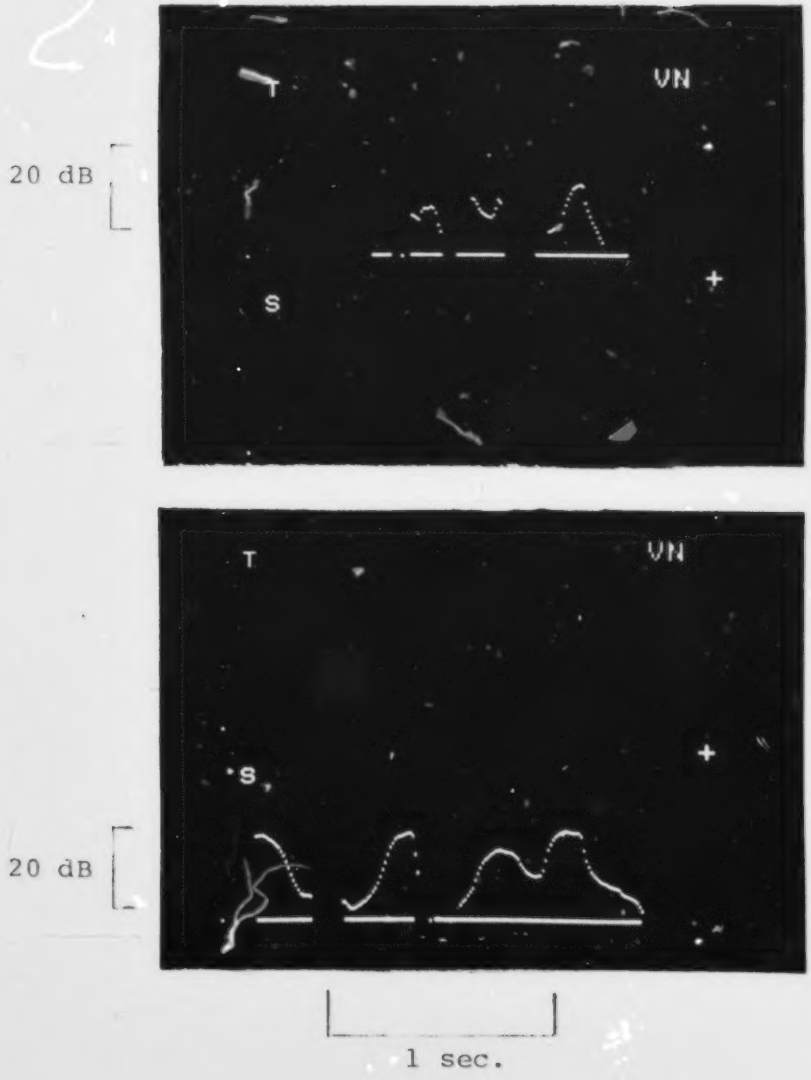

Fig. 3. Voicing-nasalization display for the sentence "You can drink your milk," as produced by a normally hearing adult (top) and a deaf student (bottom). See text.

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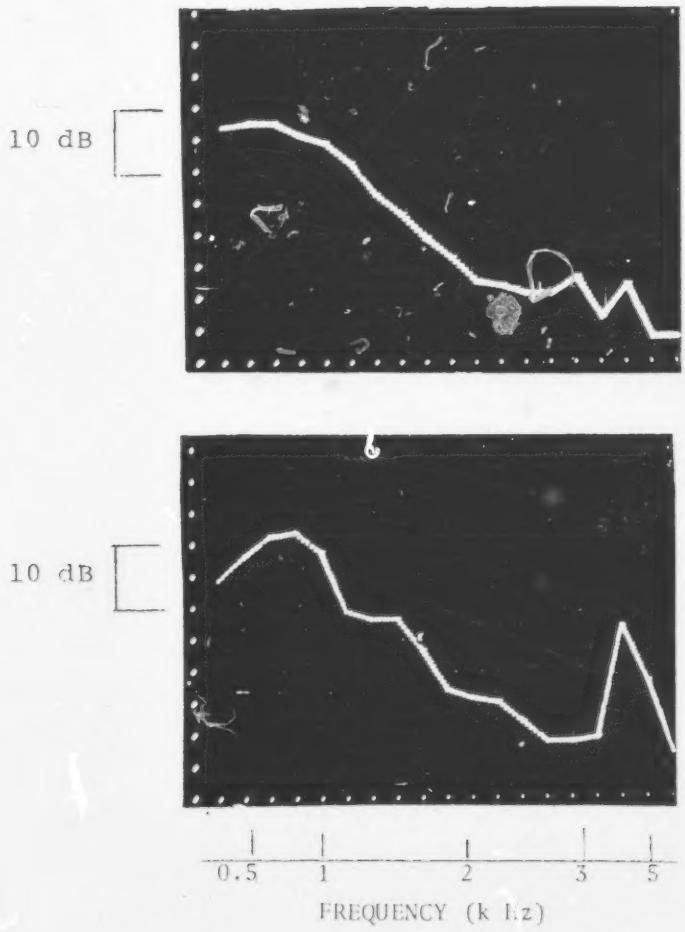

Fig. 4. Acoustic spectra (obtained from a filter bank with filter bandwidths of 360 Hz at low frequencies) for the vowel in the word four, produced by a deaf student with excessive nasalization (top) and without nasalization (bottom).

original first formant to yield the broad low-frequency peak in the spectrum. The vowel produced without nasalization has a spectrum with a better-defined formant structure, with a narrower spectral peak corresponding to the first formant. A similar observation can be made for a different child saying the word bark, in Fig. 5. Again, the first-formant region is most affected, and a low-frequency peak occurs in the apparently heavily nasalized vowel at the left. These attributes are evident in the spectrograms of the two words, which are shown above the spectra. Thus, there is a clear acoustic consequence of the lowered velum, of a type that is consistent with theoretical considerations.

SUBJECTS AND TRAINING PROCEDURES

As part of a program that is designed to evaluate the effectiveness of speech-training procedures utilizing a computer-based system of displays, 42 students at the Clarke School for the Deaf were given training on various aspects of speech for periods ranging from 7 to 28 weeks (Boothroyd, Archambault, Adams, & Storm, 1974). A subset of nine of these students received training in velar control. Some of the students concentrated on velar control for only part of the total training period, and for these students the remainder of the training sessions were devoted to other aspects of speech such as pitch control, timing, and articulation. Other students were given training in velar control for essentially their entire period of therapy. Training was administered by a research teacher in a

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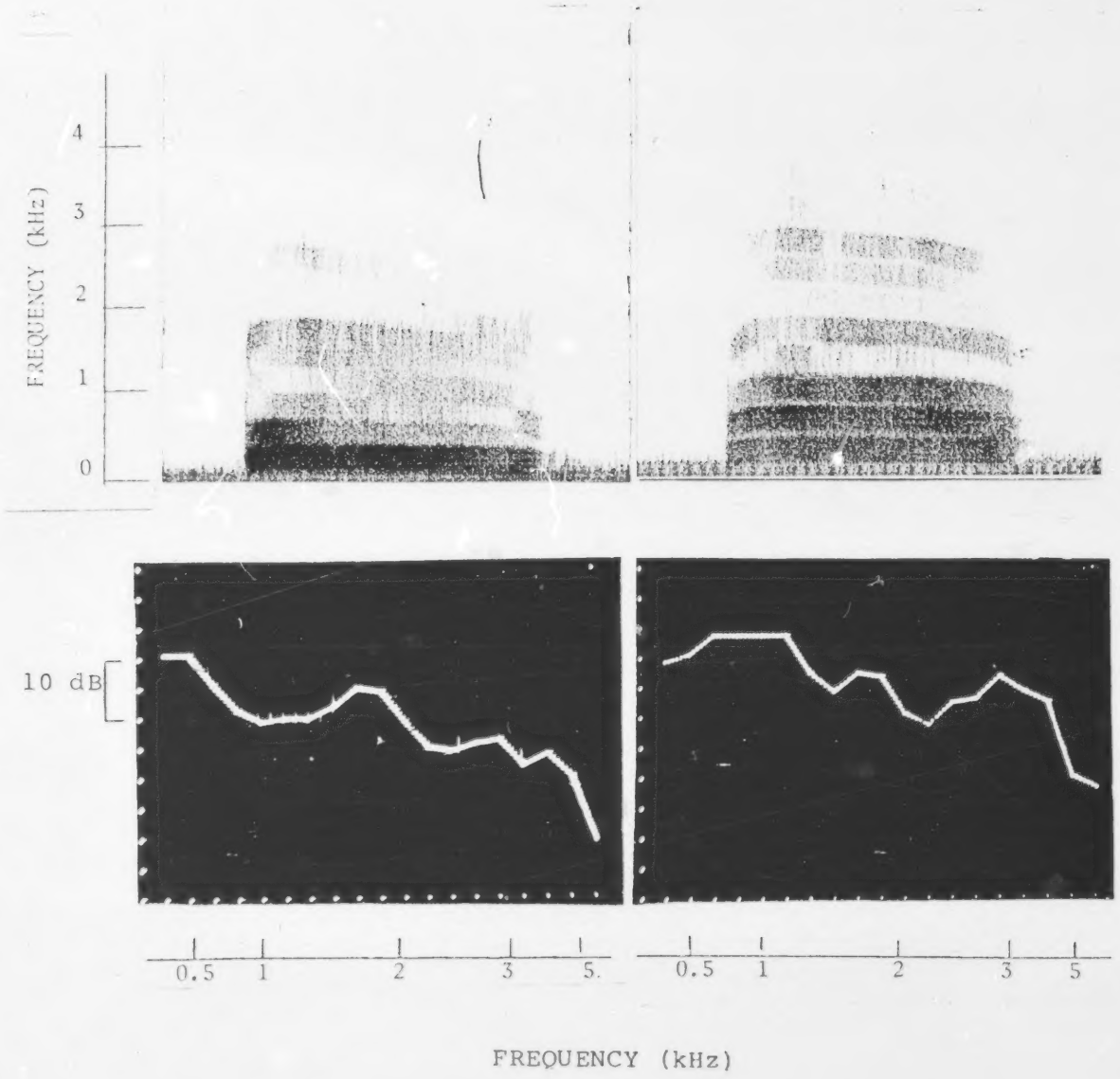

Fig. 5. Shown at the bottom are acoustic spectra of the vowel in bark, produced by a deaf student with excessive nasalization (left) and without nasalization (right). Spectrograms of the two words are displayed at the top.

one-to-one tutorial session for about 20 minutes each day. The number of such tutorial sessions devoted to training on velar control for seven of the students ranged from 25-45. Two students continued training on velar control for about 90 sessions.

The students who received therapy in velar control were 8 to 17 years of age. All had been diagnosed to have some difficulty with velar control, ranging from occasional omission of nasals in nasal-consonant clusters to severe hypernasality for essentially all vowels. This diagnosis was made initially by the students' teachers and by individuals concerned with speech training at the Clarke School. It was subsequently confirmed by measurements and observations on displays of the type shown in Figs. 1, 2 and 3.

The training sessions consisted of various types of exercises that were graded in difficulty. The general approach was to work with the student until he could achieve a reasonable level of performance in one type of exercise before proceeding to the next. The teachers used some judgment in selecting tasks for the students, however, in the interests of maintaining motivation in the students and avoiding long sessions in which the students failed to achieve successes.

The types of exercises, organized roughly in the order of increasing difficulty, are the following:

1. Sustain isolated vowels with nasalization readings below a specified criterion (as described in Stevens, Nickerson, Boothroyd, & Rollins, 1974). This exercise is performed

with several different vowels, particularly the extreme vowels /a/, /i/, and /u/.

2. Produce isolated nonnasal consonant-vowel syllables such as /pa/ or /su/ with nasalization readings below a specified criterion. This task is to be carried out with various vowels and initial nonnasal consonants.

3. Produce isolated consonant-vowel syllables with nasal consonants, the nasal consonant being fully nasalized as determined from the display. Some nasalization in the vowel is acceptable.

4. Produce isolated monosyllabic nonnasal consonant-vowel-consonant words with nasalization readings below a specified criterion.

5. Produce multisyllabic words and phrases containing no nasal consonants, with nasalization readings below a specified criterion.

6. Produce monosyllables and multisyllabic words and phrases with mixed nasal and nonnasal consonants with an appropriate time pattern of nasalization versus time. Particular attention is given to utterances containing sequences of nasal consonants and obstruent consonants.

The words and phrases in (5) and (6) were often selected to include utterances that the students were likely to use in everyday conversation in a social or school situation.

Attention was not devoted exclusively to this aspect of speech, but work on timing, articulation and pitch control was also carried out within the sessions where the principal objective was training of velar control. For example, if adequate velar control for an utterance containing both nasal and nonnasal consonants was achieved at the expense of inappropriate timing, then some attention might be given to timing in the context of proper velar control.

The experimental speech-training program in which the computer-based system of aids was used extended over a period of two years. As might be expected, the training procedures evolved and became more efficient over this period, as the teachers gained more experience with the interpretation of the displays and with training of the students utilizing the displays.

EVALUATION OF STUDENTS' PROGRESS

In general, the students were able to progress through a set of tasks, after a period of training and rehearsal on each task, using the display to assist them in exploring the consequences of various articulatory gestures and in evaluating their performance. For some students this progress was steady and consistent, whereas for others it was slow, and performance from one day to the next was erratic.

The progress of the students in the training of velar control was evaluated in several ways, including the collection and analysis of recorded speech samples before, during, and after training, and assessment of progress in particular training tasks within the training period by making measurements on the students' recorded or live utterances from time to time. In addition to objective measurements on the students' utterances, some listener evaluations of the utterances were obtained from panels of judges.

The kinds of evaluations that were obtained were designed to assess progress at three different levels:

1. Ability to perform certain speech or speechlike tasks using the display, after rehearsal of these tasks;

2. Ability to generate particular utterances without use of the display, after rehearsal of these utterances, initially with the help of the display;

3. Ability to carry over speech skills learned in the training sessions to new utterances that have not previously been practised, without using the display.

It is reasonable to assume that the ability to perform at one of these levels cannot be developed unless the skill implied by the previous level has been achieved. That is, a necessary condition for success at level (2) is to be able to perform tasks at level (1), and a necessary condition for success at level (3) is to be able to perform tasks at level (2).

During a limited period of a few weeks' training it may not be reasonable to expect substantial progress at level (3), but the realization of some progress at level (1) and possibly at level (2) is a minimum requirement in order to demonstrate some influence of the training. Thus, while the ultimate goal of speech training for deaf students is to improve the intelligibility and naturalness of the speech in spontaneous situations, progress toward this goal can be assessed by evaluating the student's performance at levels (1) and (2), as well as at level (3). The materials that have been collected and analyzed are, therefore, designed to evaluate the effectiveness of training at each of these three levels.

Assessment of Progress within Training Sessions using the Display

No formal tests, common to all students, were designed to assess progress at this level. For each student, however, records were kept to indicate performance on various kinds of tasks. Usually these records indicated how many successes or failures were achieved by a student on a particular task (such as producing an isolated vowel with nasalization below a specified criterion, or producing a nonnasal phrase with nasalization below the criterion), or they showed that a student was ultimately able to produce an utterance a specified number of times in an acceptable way.

Examples of such data are shown in Figs. 6 and 7. The student represented in Fig. 6 was initially unable to produce the vowel /a/

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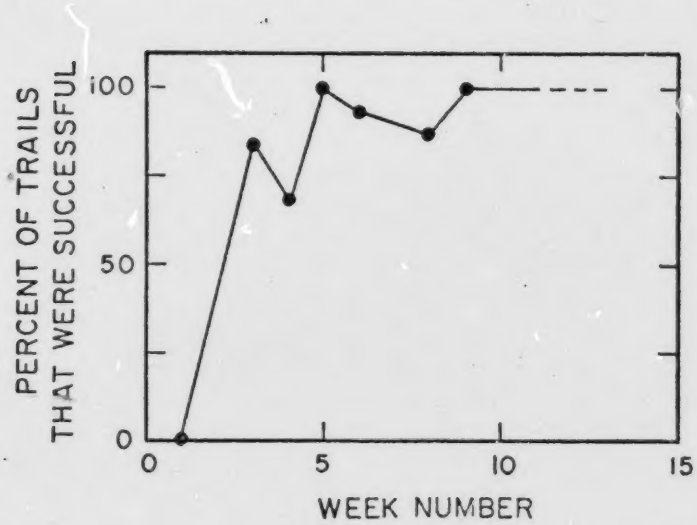

Fig. 6. Data taken from teacher's records, indicating the success of one deaf student (TB) in producing the isolated vowel /a/ with nasalization reading below a specified criterion. The abscissa is the number of weeks of training in velar control.

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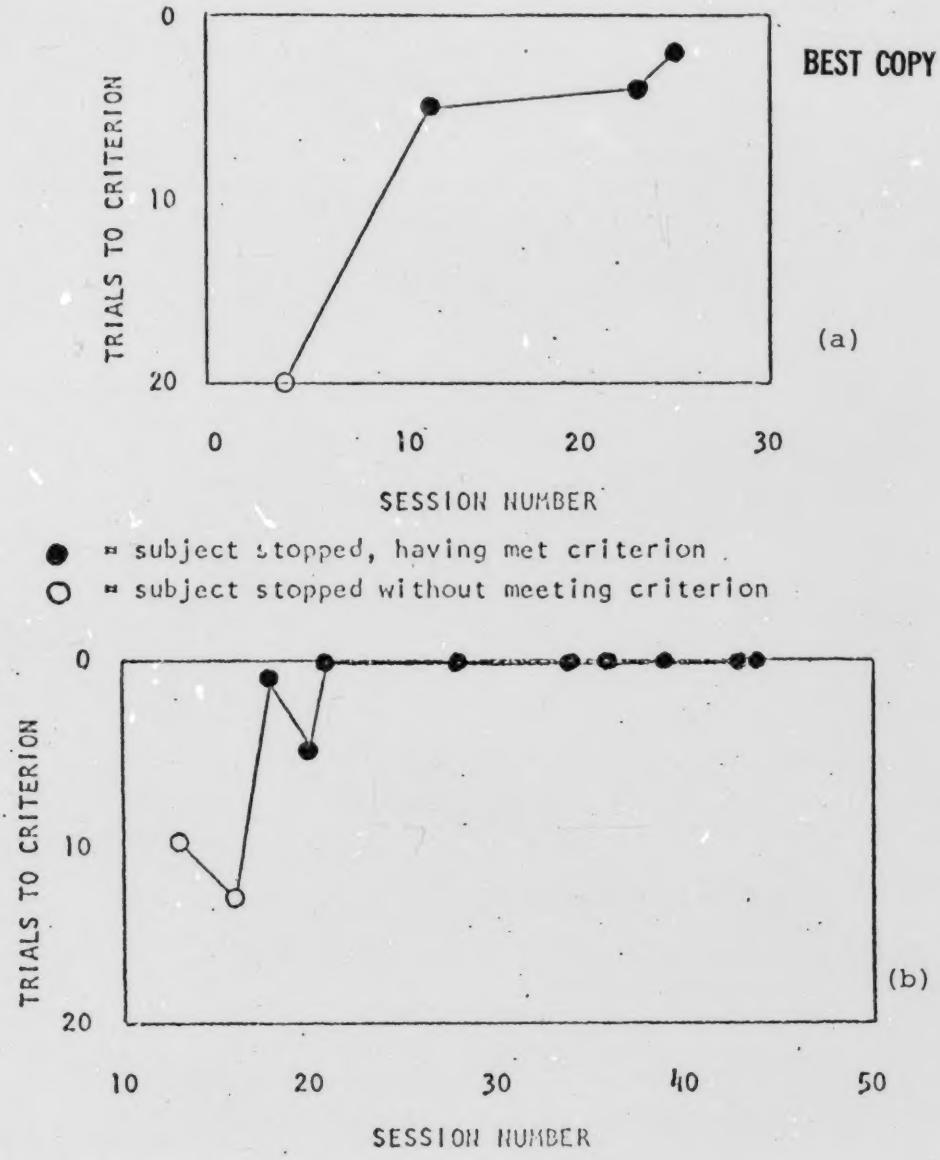

Fig. 7. a. Performance of a deaf student (JWe) in producing the word cart with nasalization reading below a specified value. The ordinate is the number of trials necessary before a criterion of five consecutive successes was achieved.

b. Same as (a), except student was LB, and the utterance was "I live at Clarke School," which contains no nasal consonants.

in isolation without nasalization. Over a sequence of training sessions, the student was given training on this task in front of the display, and her successes and failures were recorded. Beginning with Week 3, she was able to accomplish the task most of the time (with some lapses), and after Week 9 she never made an error.

Figures 7a and 7b show data for two different students, collected in a somewhat different way. In each case the criterion set for the student was to produce the utterance with an acceptable degree of nasalization (as determined objectively from the display) five times in succession. The ordinate in these graphs indicates the number of trials attempted before the criterion was met. The student depicted in Fig. 7a was attempting to produce an isolated monosyllabic word without nasalization, whereas the student represented in Fig. 7b was working with a longer nonnasal utterance. In both cases, the student was unable to reach the criterion during the early training sessions, but achieved a high level of success after a period of training. These data simply represent examples of the students' performance sampled during training sessions that involved work with a large number of utterance types and vocal gymnastics.

Of the nine students involved in this study, one had no initial difficulty in producing nonnasal vowels in isolation during the training sessions. The other eight (including the student represented in Fig. 7a) were able to achieve this task regularly within the first week of training, and sometimes within the first

session. For some of these individuals, however, there were occasional lapses in this ability during subsequent weeks of training, as Fig. 6 indicates for one student.

After several sessions of training, all of the nine students could produce simple nonnasal monosyllabic words using the display, with nasalization readings below the specified criterion, but again success was not consistent for some of the students. Most of these students were then able to proceed with nonnasal multisyllabic words and phrases. Three of the students (JWi, DL, JWe) required little rehearsal, but only needed to be reminded to think of their nasality when they spoke. Three of the students were unable to achieve success consistently with nonnasal utterances (with the help of the display) after some weeks of training, although their performance improved relative to their initial level of performance. One student (TB) never performed consistently with nonnasal phrases after 21 weeks of work. About one-half of the sentences attempted by this student could not be produced within criterion levels, even with practice. There was a tendency for sentences containing liquids, glides, and diphthongs to cause difficulty, although sentences with other speech sounds were also often produced with inadvertent jumps in nasalization.

In all cases, it should be emphasized that "success" in keeping the nasalization display below a certain criterion by no means implied adequate production of other aspects of the word or phrase. In fact, these other problems such as voice quality, timing, pitch,

and articulation were often sufficiently severe that reduction of nasalization within the vowels did not necessarily lead to a discernible improvement in the acceptability of a student's utterances, as judged informally by the teacher and by other observers.

Some students found that success in achieving adequate velar control during training sessions was more difficult for utterances containing mixed nasal and nonnasal sounds. Two of the nine students (DL, JB) did not proceed with intensive work on utterances with mixed nasal and nonnasal sounds (training was switched to timing problems), and one (JWi) was able to produce such utterances with adequate velar control when she was reminded of this aspect of her speech. Of the remaining students, two were able to succeed for most short phrases and sentences after a period of practice, using the display (JWe, LB). The remaining four students (JS, DD, TB, AM) could produce an acceptable pattern on the nasal display for certain utterances (more than 50 percent) consistently and for other utterances sporadically, while they failed to meet the criterion for utterances with some combinations of sounds. Sometimes the criterion could be met only with slowly articulated speech, and velar control became erratic for faster rates of talking.

Evaluation Based on Pre- and Post-Training Recordings

Before training was commenced, a series of utterances was recorded for each student involved in the training program. The recordings were made on two channels--one channel was the microphone

signal, and the other was the signal from the accelerometer attached to the nose. The recorded material consisted of (1) a list of 33 monosyllabic words, each elicited from the students by showing a picture; (2) a series of short phrases and sentences; (3) an approximation to spontaneous speech obtained by having the student tell the story described by a sequence of pictures; and (4) a list of six ten-word sentences drawn from a larger list that is used routinely to evaluate the intelligibility of students at the Clarke School (Magner, 1972). The same set of material was recorded within a few days after speech training with the system was terminated.

Objective Measurements

From the monosyllabic words, a subset of 21 was selected for the objective assessment of problems with velar control. This list of words, which is given in Table 1, includes ten nonnasal words in which the vowel nuclei consist of ten different nonnasal vowels, and 11 words with nasal consonants in various positions in the word. The phrases and sentences that were examined from the point of view of velar control are listed in Table 2. The first of these items has no nasals, the second and third have a number of nasal consonants with no intervening obstruent consonants, and Items 4, 5 and 6 contain mixed stops and nasals.

A series of measurements and observations was made on these recorded words, phrases, and sentences, along lines discussed previously (Stevens, Nickerson, Boothroyd, & Rollins, 1974). For

Table 1. List of words recorded by deaf students before and after training.

Nonnasal Words	Vowel	Nasal Words
lead	i	mouth
dish	ɪ	nail
dress	ɛ	arm
flag	æ	spoon
socks	ɑ	queen
glove	ʌ	clown
straw	ɔ	ring
church	ɚ	snow
book	ʊ	jump
shoe	u	hand
		think

Table 2. List of phrases and sentences that were examined for adequacy of velar control when produced by deaf children.

1. You lost your glove?
2. My money.
3. Many men are in Maine now.
4. You can drink your milk.
5. I went home Friday night.
6. A spoon and a dish.

each student, the peak accelerometer output (in dB) was obtained within the nasal consonant for each of the words containing such a consonant. From this group of measurements, readings for well-formed nasal consonants were selected, a fixed objective criterion being used as a basis for rejecting a consonant that was not adequately nasalized. Average values of accelerometer output for the well-formed nasal consonants from each student were computed. Then the peak accelerometer output for each of the vowels in the nonnasal words was obtained, and the difference between this value and the average value for the nasal consonants was determined for each vowel spoken by each student. These differences were compared with similar differences previously determined for normally-hearing children, and on the basis of this comparison each vowel was assessed as being produced with or without excessive nasalization.[2] Thus for each deaf student, the objective measurements indicated which vowels were produced with excessive nasalization, and which nasal consonants were produced with inadequate nasalization.

Measurements of a similar kind were made on the phrases and sentences. These measurements were also aimed at obtaining the difference in accelerometer output for nasal consonants and for vowels that should have produced without nasalization. Two such difference measures were obtained as follows:

Measure N_1: The accelerometer output was measured for each well-formed nasal consonant in Sentences 2 and 3 in Table 2, and the average of these measurements was determined. A similar measure

was obtained for each vowel in Sentence 1, and an average for these vowels was determined. N_1 is defined as the difference between these two measurements for nasals and for vowels that should have been produced without nasalization.

Measure N_2: The accelerometer output was determined for the nasal consonant giving the maximum reading in each of Sentences 4, 5 and 6, and the average of these readings was calculated. Within each of these sentences a vowel surrounded by obstruent consonants (or by the sentence boundary) was selected, since such a vowel should be produced with a raised velum by normally-hearing speakers. The syllables in which these vowels occurred were You (Sentence 4), Fri (Sentence 5), and dish (Sentence 6). The average accelerometer output for these vowels was obtained. Measure N_2 is the difference between the average readings for the nasals and the nonnasal vowels.

The data from the nine students showed no systematic differences between N_1 and N_2, and, consequently, for the purposes of this analysis, the average value $N = \frac{1}{2}(N_1 + N_2)$ was used to provide an objective indication of adequacy of velar control. For a normally-hearing speaker with no obvious speech problems, this difference would be about 15 dB. (It should be noted that this measure N is a sensitive indicator of whether vowels that should be produced with a raised velum are in fact produced that way, i.e., it tends to measure the degree of hypernasality. It is not a particularly sensitive indicator of the adequacy of velar control

for nasal consonants, i.e., it is not a good measure of the degree of hyponasality.)

The results of the measurements on speech samples recorded before and after training are displayed in the first two rows of Fig. 8. One observes, first of all, the marked differences in overall adequacy of velar control at the beginning of training (at least as determined by these objective measures) from one student to another. For example, students JB, LB, DD, AM, and JS all produced at least eight (out of ten) vowels in monosyllabic nonnasal words with excessive nasalization. For all of these students, the difference in peak nasalization for nasals and for nonnasal vowels in sentences was less than 6 dB. Other students, on the other hand, were closer to the normal 15-dB difference, although all students clearly had some problems with velar control. Thus, the informal subjective evaluations of the teachers and research staff that led to selection of these students for training in velar control were borne out by the objective data. (In this study, the measurements from the pre-training recordings were usually made some time after training commenced. A more desirable procedure would have been to obtain these objective assessments before training, since these data can be used to guide the formulation of training objectives and procedures. This procedure was in fact followed for students who participated in the latter part of the training program described here.)

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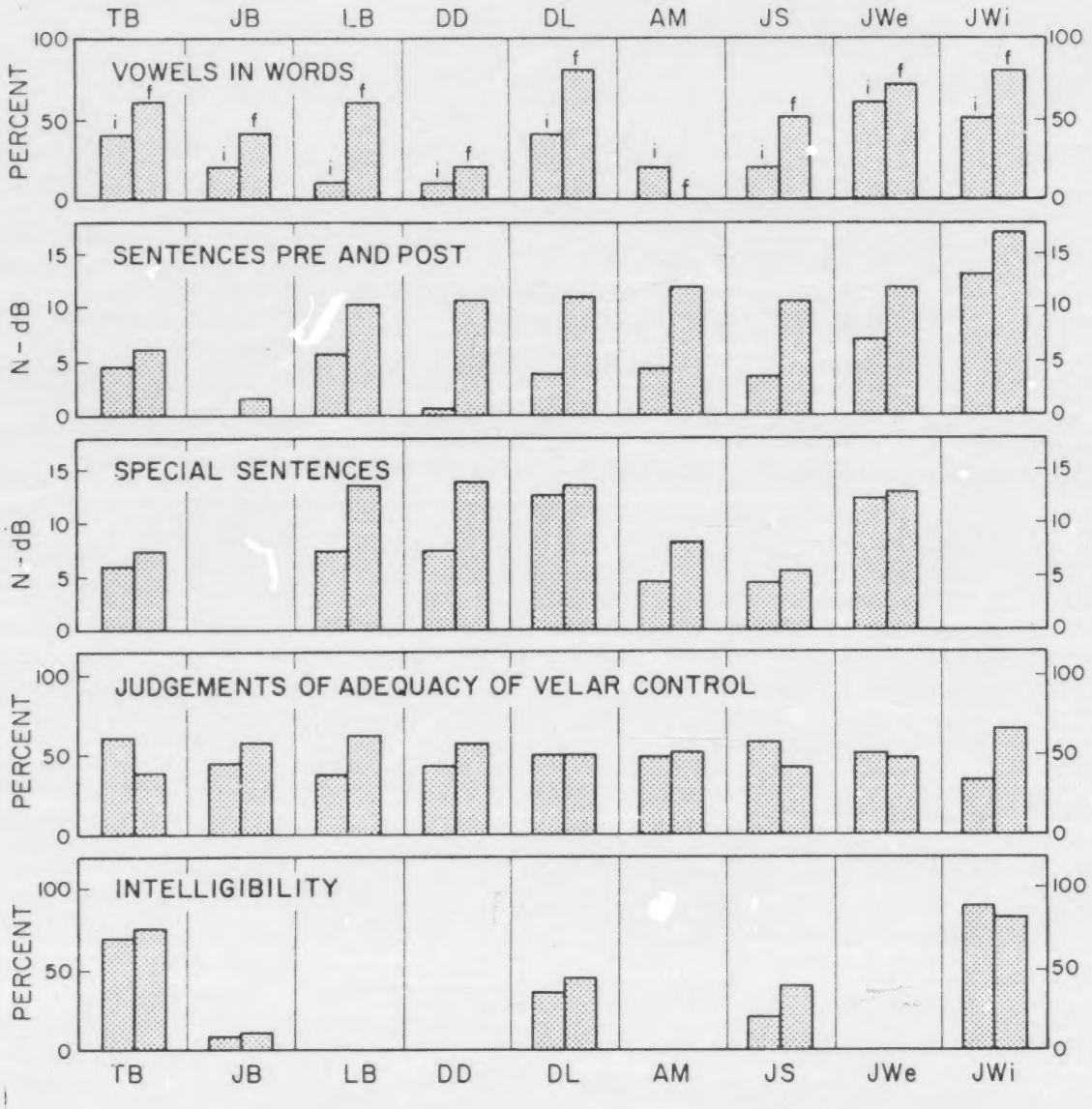

Fig. 8. Legend on the following page.

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Fig. 8. Objective data and subjective judgments for speech of nine deaf students who received training in velar control. Left-hand bar in each case represents speech sampled before training (or early in training period); right-hand bar represents speech sampled after training (or later in training period). Upper panel represents percent of vowels in nonnasal monosyllabic words produced with adequate velar control. Next two panels represent nasalization index N for sentences recorded before and after training and for special speech sample recorded on two occasions during training. Judgments of adequacy of velar control indicate percent of listeners judging initial or final speech sample to have the more adequate velar control. Intelligibility is based on data from read sentences and spontaneous speech. For some measures, data were not collected for all students. See text.

Figure 8 indicates that several students showed significant improvement in velar control based on both kinds of measures, whereas for others the gain was small and probably insignificant. For example, LB, DL, and JS could all be considered to have demonstrated substantially improved velar control during the production of vowels, both in isolated words and in sentences. Student JB began and finished training with very poor velar control. Although he was able to show progress in certain exercises in the training sessions with the aid of the display, this progress apparently did not carry over into unrehearsed material without the display. Other students could be regarded as achieving an intermediate degree of success. The two students who had the least severe problems at the onset of training (JWe and JWi) showed some improvement on both measures, although the amount of improvement was not large, presumably because the available degree of improvement was limited. Students AM and DD continued to have difficulty in producing isolated nonnasal words, but did have some success in producing vowels with less nasalization in phrases and sentences. In spite of an extended period of training (21 weeks), TB showed only modest improvement in velar control as assessed by these measures.

Subjective Evaluations of Nasality

An attempt was made to obtain a subjective evaluation of the adequacy of velar control for the pre- and post-training recordings of the six phrases and sentences listed in Table 2. The two

recordings of each utterance obtained before and after training were arranged in pairs, and an initial listening test consisting of all of these pairs for all students was prepared. Each pair appeared twice in the test, once in each order. This test was presented to a group of four judges who had experience in listening to the speech of the deaf. The judges were told what the sentences were to be, and were asked to determine which member of the pair had the more adequate velar control.

The results reinforce the well-known observation that listener judgments of nasality show large individual differences, and often appear to be based on aspects of the speech other than velar control (Bradford, Brooks, & Shelton, 1964; Colton and Cooker, 1968). For only two of the students (JWi and DD) did the judged adequacy of velar control show significant improvement. For the remaining students the judgments of pre- and post-training recordings showed no significant change in adequacy of velar control.

The judges found the task of evaluating the adequacy of velar control when presented with a pair of sentences only once to be an extremely difficult one. For this reason, and because of the large differences among their responses, it was decided to conduct a second, and more elaborate, listening test. In this case each listener was allowed to listen to each pair of utterances (the before- and after-training samples of a given sentence spoken by a given child) as many times as he wished before selecting the one that he thought showed the best velar control. In addition to selecting the better of the two utterances, the listener also

indicated his degree of confidence in his choice of a three-point scale: "very certain," "moderately certain," "uncertain."

The speech samples were recorded on Language Master cards. One channel of each card contained a before-training sample and the other channel contained the corresponding after-training sample. Before- and after-training samples were randomly distributed between the two channels, and, of course, listeners were not told which channel contained which sample. Each of 15 judges listened to 54 before- and after-training pairs, 6 pairs for each of the 9 students. All of the listeners were familiar with the speech of the deaf. They were instructed to attempt to judge the utterances solely on the basis of adequacy of velar control, and to ignore other aspects of the speech. The response sheets that were used indicated what the child had attempted to say for each utterance.

The primary purpose for conducting this test was to determine whether the after-training speech samples were perceptibly different from the before-training samples in terms of adequacy of velar control. The results are also interesting, however, as they relate to the question of what nasality means perceptually, and whether one can hope to obtain reliable listener judgments of this aspect of speech. In what follows, we discuss the results from both of these perspectives.

For 33 of the 54 pairs of utterances, the majority of the 15 judges selected the after-training sample as the better of the two. The difference is not large, but it is in the right direction,

and it is significant by sign test at about the .05 level. Thus, we conclude that in the aggregate, training did have a small positive effect on velar control, insofar as adequacy of velar control is perceptually determinable.

The results of the listener judgments were analyzed for each student and compared with the objective measurements described above. The fourth row of Fig. 8 shows the percentage of judgments that ranked the initial recordings (left bar) or final recordings (right bar) superior from the point of view of velar control for each student. While the students who showed relatively large improvements in terms of objective measures (averaged over all sentences) tended also to be judged by the listeners to have improved, there were some obvious exceptions. JS, for example, who improved considerably in terms of objective measures showed no improvement according to the listener judgments. A more detailed examination was made of the four utterances that contain nonnasal vowels (Items 1, 4, 5 and 6 in Table 2), and pairs were selected for which the measured reduction in nasality for the nonnasal vowels in the post-training recordings compared with the pre-training recordings was at least 10 dB, based on the accelerometer output. Of the 9 pairs (out of 36) that met this criterion, 7 were judged by the majority of listeners to represent an improvement in velar control. Thus there is some evidence for correlation between subjective judgments and objective measures. (Careful listening to the two utterances for which the pre-training version was judged

to be better [both utterances were "a spoon and a dish"] suggested that, whereas the velum was apparently closed in the word dish in the post-training versions but not in the pre-training ones, there were other aspects of the utterance relating to velar control and timing in the two words "a spoon" that evidently convinced the listeners to judge the pre-training utterance to be superior.)

Perhaps the most discouraging aspect of the results, from the point of view of methodology, is the fact that listeners differed greatly in their evaluations of the speech. Several of the listeners commented spontaneously that they found the task difficult. Nevertheless, the "very certain" rating was used more frequently (38% of the trials) than either of the other ratings. ("Moderately certain" and "uncertain" were used on 35% and 27% of the trials, respectively.) No attempt was made to quantify the degree of consensus among the listener judgments; however, inspection of the response sheets revealed a great deal of disagreement. For 10 of the 54 sentences judged, for example, at least three listeners chose one alternative with a "very certain" rating, while at least three others chose the opposite alternative with the same high degree of confidence. It appears that not only is the appropriateness of velar control a difficult thing to judge perceptually, but listeners who are highly familiar with speech of the deaf may disagree concerning the relative quality of speech samples in this regard, even when they feel that the difference is sufficiently great to make the judgment a relatively easy one.

Intelligibility Estimates

The ultimate goal of speech training of the deaf is, of course, to develop more intelligible and natural-sounding speech, thus enhancing the ability of the deaf individuals to communicate with normally-hearing people. As noted above, the pre- and post-training recordings for each student included samples of spontaneous speech, and a list of six sentences (a different list for each student) that were designed to evaluate the intelligibility of the students. Estimates of intelligibility from these recorded materials were not obtained systematically for all students, since the principal emphasis in this study was to evaluate progress in improving just one aspect of the student's speech, and it was not anticipated that the intelligibility estimates would be sufficiently precise that significant improvements in scores would be detectable.

However, five of the nine students were included as part of another study in which intelligibility measures were related to other objective measures and subjective evaluations of the students' speech. Results for these students are reported here to indicate the kinds of findings that might be expected from pre- and post-training intelligibility measures based on this type of material. Recordings of the spontaneous speech and the 10-word sentences of these students were evaluated by four listeners who were experienced in listening to the speech of the deaf and by eight "naive listeners" (listeners who had little or no prior exposure to speech

of the deaf). For the spontaneous speech an intelligibility measure based on the number of "content" words heard correctly was determined for each listener group. An approximation to the "correct" utterances of the students was obtained from transcriptions prepared by the teacher who was sitting with the student while the sequence of pictures was being described. An average intelligibility measure for both pre-training and post-training recordings was obtained by averaging the four numbers (two types of speech material, two groups of listeners).

The results for these five listeners are displayed at the bottom of Fig. 8. The data show some improvement in intelligibility for four of the five students, but, except possibly for one individual, the improvement could not be considered substantial.

Training and Performance with Rehearsed Words and Phrases

For seven of the students, a procedure was developed for assessing progress within the training sessions using speech material that was specially selected for each student. For each of these students, a different set of 6-10 phrases or words was chosen, some utterances being common to the lists of more than one student; this was called the special speech sample. Some of these words or phrases contained no nasal consonants, and others included mixed nasal and obstruent consonants. An initial recording of these utterances was made within three weeks after training in velar control had commenced. During the following weeks, training in velar

control for these utterances was included in the tutorial sessions utilizing the display, along with training involving a variety of other exercises and utterances. Toward the end of the training period, another recording of the special speech sample was made. For some students, a recording was also obtained at some point within this training period. The utterances for these recordings were all produced without the display, whereas the training sessions utilized the display, usually in flow mode, and sometimes in delay mode.

The recordings were subjected to analysis of the type carried out on the phrases and sentences that formed the initial speech sample. In particular, the mean difference between the nasalization readings in the well-formed nasal consonants and the nasalization readings in the vowels in the sample that should have been nonnasal was obtained for each recording of each student. These differences are comparable to the average of the N_1 and N_2 measures noted above.

The results for the initial and final special speech sample for each student are summarized in the third row of Fig. 8. Comparison of this nasalization measure for the initial special speech sample with that for the initial pre-training phrases and sentences (Column 2 of the figure) shows that the performance on the special sample was equal to or better than that on the pre-training sample. This difference might be ascribed to the fact that the brief period of training before the special sample was recorded might have led to some improvement in velar control, either as a result of newly

acquired skills or a result of greater awareness of and adherence to previously acquired skills. Some improvement from the initial to the final special speech sample was observed for all seven students from whom this measure was obtained. For some, the gain was small and possibly insignificant (JL, JS, JWe), whereas there was an apparent marked improvement for others (LB, DD). It could not be concluded, however, that the special speech sample consisting of rehearsed material showed greater improvement, on the average, than unrehearsed material recorded before and after training. It might be speculated that, since performance on the special speech sample was already above that for the pre-training sample, there was less room for improvement for the rehearsed material than for the unrehearsed material. On the final measurement for the rehearsed sample, several students came close to the 15-dB nasalization measure that would be expected from normally-hearing speakers.

STEPS TOWARD IMPROVED EFFICIENCY OF TRAINING

As the speech training and evaluation program described above progressed, it was recognized that training with the aid of the display was contributing substantially to the ability of the students to improve velar control during the training sessions using the display to provide immediate feedback. However, insufficient attention was being devoted to carryover of the skills to communication situations where the display was not available to the student. Furthermore, there was concern that a brief 20-minute period of

exposure to training with the system each day for a limited number of weeks did not often provide the student with sufficient practice on the skills learned in the tutorial sessions. During the latter part of the program, two steps were taken to improve the efficiency of speech training with the system and to accelerate the carryover process.

Self Evaluation

One of these steps was to motivate the student to judge the adequacy of his utterances without relying on the display. After the student had gained experience with interpretation of the display and had achieved an adequate level of success with a particular type of utterance using the display to provide immediate knowledge of results, the delay mode of display was selected. After an attempt at producing an utterance with the system in this mode, the student was asked to judge the adequacy of his production before the display was shown. The display was then produced, and the correctness of the student's evaluation was determined and recorded.

The students were generally able to improve their ability to judge the adequacy of velar control without referring to the display. An example of data collected for one student is shown in Fig. 9. The student was asked to produce a phrase without nasalization, and then, before the display was presented, to judge whether the velar control in the utterance was adequate.

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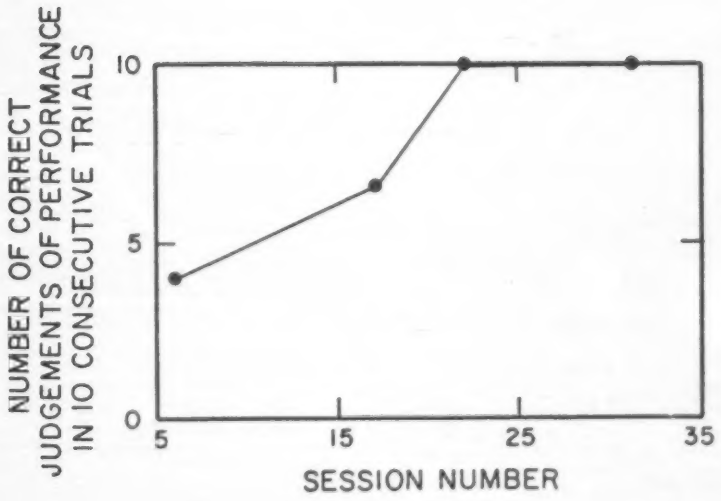

Fig. 9. Showing the ability of one student (LB) to judge the adequacy of her production of the sentence "I live at Clarke School" without using the display. The performance of the student is sampled at several occasions throughout training, as indicated on the abscissa.

Such a judgment was also made by the teacher, based both on subjective impression and on subsequent inspection of the display. The percent of time (in a sequence of 10 consecutive trials) that the student made a correct assessment of her attempt (i.e., an assessment that corresponded to that of the teacher) was determined, as shown in the figure. It is evident that, after a period of time, this student could consistently evaluate her own utterances with respect to velar control.

During the latter phases of the training program, this procedure was followed for a number of the students. Insufficient data are available, however, to indicate the extent to which this type of activity accelerated the ability of the students to carry over the skills learned in the training sessions to their spontaneous speech.

Unsupervised Drill

After a period of one-to-one tutoring with a teacher, most students developed an ability to understand and to interpret the details of the display, and thus to assess whether a given utterance was produced with proper control of the speech activity that was the focus of the training. During the latter part of the program, it was decided that some students should be able to practice with the aid of the computer system without direct supervision from the teacher. A procedure was developed where the students could sign up for time with the system on an

unsupervised basis. The unsupervised drill consisted for the most part of material covered previously in one-to-one tutorial sessions. Some students developed the facility to turn on the computer, read in programs, and to prepare their own exercises for drill. These drill sessions were interspersed with occasional sessions with the teacher.

Six students in the speech-training program utilizing the computer-generated displays participated in some sessions of unsupervised drill. One of these students $(LB)^3$ was receiving training in velar control. Although there were insufficient data to assess the success of this unsupervised component of the training, it can be reported that the students responded positively and with good motivation to this activity.

DISCUSSION AND CONCLUSIONS

There is little doubt that the use of a display of the type discussed here can help both the student and the teacher to evaluate objectively the adequacy of velar control in an utterance. This capability represents an improvement over the conventional training procedure in which the teacher must make a judgment of the adequacy of velar control for a student's utterance, and then communicate this evaluation to the student. Subjective judgments of nasality are highly variable, as has been demonstrated in the past (Bradford, Brooks, & Shelton, 1964), and as has been confirmed in the experiments in this study.

It is clear, furthermore, that with the aid of the display during training sessions, most students can produce utterances with improved control of the velum, compared with their performance before training.

On the basis of the limited data available from this study, speech material recorded at different times before, during, and after training shows improvement in velar control for most students, at least based on objective measurements of the output of the accelerometer attached to the nose. This positive result is, however, tempered by the finding that the adequacy of velar control as evaluated by listeners did not show improvement for most students, and that gains in intelligibility could not in general be observed.

This minimal gain in subjectively determined aspects of speech may be due in part to the fact that judgment of these aspects (including judgments of velar control) are influenced by many different physical attributes of the speech of the deaf. Improvement in just one of these attributes may not be sufficient to influence significantly some overall subjective judgment. Furthermore, it is possible that improvement in one aspect of speech may be achieved by relaxing (at least temporarily) some other attribute. The tutored program described here was structured in such a way that primary emphasis for a given student was usually placed on just one aspect of his speech.

These findings emphasize the importance of devising more effective and more efficient training procedures that will

accelerate the acquisition and carryover of speech skills. Efforts need to be expended in exploiting the potential of self-evaluation and unsupervised work along lines indicated above. The results of this study suggest, however, that a system that includes a display of the type described here can be incorporated effectively into the training of deaf students to achieve proper control of their velum.

NOTES

1. The term "nasality" is often used to describe a particular quality of an individual's voice, as judged by listeners. Listener judgments of this quality show large individual differences, suggesting that different people are basing their judgments on different aspects of the speech. Furthermore, there appears to be no clear acoustic or articulatory parameter that is correlated with this subjective quality of nasality. This ill-defined use of the term nasality will be avoided here. Rather, the output from the nasal accelerometer for a given speaking level will be said to indicate the degree of "nasalization" of a sound. This output presumably provides an indication of the amount of acoustic coupling to the nasal cavities during voiced sounds, and, hence, for a given speaking level, provides a measure of the size of the velopharyngeal opening (see Stevens, Nickerson, Boothroyd, & Rollins, 1974).

2. The criterion selected was such that 85 percent of normally-hearing children would lie within the criterion for each vowel, i.e., 15 per cent of normally-hearing children would be considered to have excessive nasalization in the vowel by this criterion.

3. The results for this student in Fig. 8 were based on pre- and post-training speech recordings made before she began unsupervised drill.

ACKNOWLEDGMENTS

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